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Syntactic Congruences of some Codes

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Abstract

We consider syntactic congruences of some codes. As a main result, for an infix code L , it is proved that the following (i) and (ii) are equivalent and that (iii) implies (i), where P_L is the syntactic congruence of L .

(i) L is a P_{L^2} -class.

(ii) L^m is a P_{L^k} -class, for two integers m and k with $1 \leq m \leq k$.

(iii) L^* is a P_{L^*} -class.

Next we show that every (i), (ii) and (iii) holds for a strongly infix code L . Moreover we consider properties of syntactic congruences of a residue $W(L)$ for a strongly outfix code L .

Keywords: prefix code, suffix code, infix code, syntactic congruence

1 Introduction

The theory of codes has been studied in algebraic direction in connection to automata theory, combinatorics on words, formal languages, and semigroup theory. A lot of classes of codes have been defined and studied ([1], [2]). Among those codes, prefix codes, suffix code, bifix codes, infix codes and outfix codes have many remarkable algebraic properties ([2], [3], [4]). Recently a strongly infix code and a strongly outfix code were defined and the closure property under composition operation for these code was proved ([5][6]).

In this paper we study syntactic congruences of some codes, especially, (strongly) infix codes and (strongly) outfix codes. Several properties of the syntactic congruence P_L of L , for L infix or outfix, have been presented in [2] and [3] and moreover some interesting characterizations have been presented on the syntactic monoid and the syntactic congruence P_L of L for an infix code L ([7]). We mainly deal with the syntactic congruence P_{L^n} of L^n , $n > 1$, and P_{L^*} of L^* in this paper below.

In section 2 some basic definitions and results are presented.

In section 3, first we prove that the following (i) and (ii) are equivalent for an infix code L , and that (iii) implies (i), where P_L is the syntactic congruence of L .

- (i) L is a P_{L^2} -class.
- (ii) L^m is a P_{L^k} -class, for two integers m and k with $1 \leq m \leq k$.
- (iii) L^* is a P_{L^*} -class.

Next we show that every (i), (ii) and (iii) holds for a strongly infix code L , and moreover we show that L^* is contained in a $P_{W(L^*)}$ -class, where $W(L)$ is a residue of L . Last we consider a relation between P_{L^n} -class and $W(L)$ for a strongly outfix code L .

2 Preliminaries

Let Σ be an alphabet. Σ^* denotes the free moniod generated by Σ , that is, the set of all finite words over Σ , including the empty word 1, and $\Sigma^+ = \Sigma^* - 1$. For w in Σ^* , $|w|$ denotes the length of w .

A word $x \in \Sigma^*$ is a *factor* or an *infix* of a word $w \in \Sigma^*$ if there exists $u, v \in \Sigma^*$ such that $w = uxv$. A factor x of w is *proper* if $w \neq x$. A catenation xy of two words

x and y is an *outfix* of a word $w \in \Sigma^*$ if there exists $u \in \Sigma^*$ such that $w = xuy$. A word $u \in \Sigma^*$ is a *left factor* of a word $w \in \Sigma^*$ if there exists $x \in \Sigma^*$ such that $w = ux$. A left factor u of w is called *proper* if $u \neq w$. A right factor is defined symmetrically. An outfit xy of w is *proper* if $xy \neq w$. The set of all left factors (resp. right factors) of a word x is denoted by $Pref(x)$ ($Suf(x)$).

A language over Σ is a set $L \subseteq \Sigma^*$. A language $L \subseteq \Sigma^*$ is a *code* if L freely generates the submonoid L^* of Σ^* (See [1] about the definition.). A language $L \subseteq \Sigma^+$ is a *prefix code* (resp. *suffix code*) if no word in L has a proper left factor (a proper right factor) in L . A language $X \subseteq \Sigma^+$ is a *bifix code* if L is both a prefix code and a suffix code. A language $L \subseteq \Sigma^+$ is an *infix code* (resp. *outfix code*) if no word $x \in X$ has a proper infix (a proper outfit) in L .

A language $L \subseteq \Sigma^+$ is *in-catenatable* (resp. *out-catenatable*) if a catenation of two words in L has a proper infix (proper outfit) in L which is neither a proper prefix nor a proper suffix. Formally, L is in-catenatable if there exist $u_1, u_2, u_3, u_4 \in \Sigma^+ - X$ such that u_1u_2, u_3u_4 and u_2u_3 is in L , and L is out-catenatable if there exist $u_1, u_2, u_3, u_4 \in \Sigma^+ - X$ such that u_1u_2, u_3u_4 and u_1u_4 is in L with $u_1u_2 \neq u_3u_4$. A language $L \subseteq \Sigma^+$ is a *strongly infix code* (resp. *strongly outfit code*) if L is an infix code (outfix code) and is not in-catenatable (out-catenatable). A strongly infix (resp. outfit) code may be abbreviated to an *s-infix* (*s-outfix*) code.

Let M be a monoid and let N be a submonoid of M . Then N is *right unitary* (resp. *left unitary*) in M if for all $u, v \in M$, $u \in N$ and $uv \in N$ ($vu \in N$) together imply $v \in N$. The submonoid N is *biunitary* if it is both left and right unitary. The submonoid N is *double unitary* in M if for all $u, x, y \in M$, $u \in N$ and $xuy \in N$ together imply x and $y \in N$. The submonoid N is *mid-unitary* in M if for all $u, x, y \in M$, $xy \in N$ and $xuy \in N$ together imply $u \in N$.

Proposition 1 [1] *Let $L \subseteq \Sigma^+$ be a code. A language L is a prefix code (resp., suffix code, bifix code, s-infix code) iff L^* is right unitary (left unitary, biunitary, double unitary).*

Proposition 2 [6] *Let $L \subseteq \Sigma^+$ be a code. If a language L is a strongly outfit code, then L^* is mid-unitary.*

Proposition 3 *Let $L \subseteq \Sigma^+$ be a code. If L^* is mid-unitary, then L is an outfit code.*

Proof. Suppose that L would not be outfix with L^* mid-unitary. There exist $x, y \in \Sigma^*$ and $u \in \Sigma^+$ such that both xuy and xy are in L . Since L^* is mid-unitary, we have that $u \in L^*$, and thus $u \in L^+$. It is easily obtained that both uyx and yxu are in L^* , since both xuy and $xuyxuy$ are in L^* . Thus $uyxu$ has two factorization. This contradicts the fact that L is a code. \square

For a language L over Σ and u in Σ^* , let

$$L..u = \{(x, y) | x, y \in \Sigma^* \text{ and } xuy \in L\}.$$

The *syntactic congruence* P_L is defined by

$$u \equiv v(P_L) \quad \text{iff} \quad L..u = L..v.$$

The *syntactic monoid* $Syn(L)$ of L is the quotient monoid Σ^*/P_L . For any language $L \subseteq \Sigma^*$, let $W(L)$ denote the *residue* of L , that is,

$$W(L) = \{u \in \Sigma^* | L..u = \phi\}.$$

3 Syntactic congruences of some codes

In this section we consider properties of syntactic congruences of some codes.

Before discussing, we give some basic results.

Proposition 4 [3] *Every infix code L is a P_L -class.*

Proposition 5 [3] *Let L be an outfix code. Then every P_L -class different from $W(L)$ is an outfix code.*

Lemma 6 *For languages $L, K \subseteq \Sigma^*$, if L is a P_K -class, then $P_K \subseteq P_L$.*

Proof. Suppose that L is a P_K -class, and that $u \equiv v(P_K)$. Then one has that $xuy \equiv xvy(P_K)$ for every x, y . If xuy is in L , then it is in a class of P_K . Thus xvy is in the same class of P_K , that is, in L . Similarly we can easily obtain that $xvy \in L$ implies $xuy \in L$. Hence $u \equiv v(P_L)$. \square

Lemma 7 *Let L be a code, and let m and k be integers with $1 \leq m \leq k$. If $u \in L^m$, $xuy \in L^k$ and $x, y \in L^*$, then $x \in L^i$ and $y \in L^j$ for integers $i, j \geq 0$ such that $i + j = k - m$.*

Proof. Let $u = u_1 \dots u_m$; $u_1, \dots, u_m \in L$, $xuy = v_1 \dots v_k$; $v_1, \dots, v_k \in L$,

$x = a_1 \dots a_i$; $a_1, \dots, a_i \in L$, and $y = b_1 \dots b_j$; $b_1, \dots, b_j \in L$. Since L is a code, $a_1 = v_1, \dots, a_i = v_i$; $u_1 = v_{i+1}, \dots, u_m = v_{i+m-1}$; $b_1 = v_{i+m}, \dots, b_j = v_{i+m+j}$. It is obvious that $i + m + j = k$. Thus the result holds. \square

Lemma 8 *For a languages L and K , if $P_L \subseteq P_K$ and K is contained in a P_L -class, then K is equal to a P_L -class.*

Proof. It is obvious from the fact that L is a union of P_L -classes. \square

Now we consider properties of a syntactic congruence P_{L^n} of L^n and a syntactic congruence P_{L^*} of L^* for an infix code L and a positive integer n . The first result holds for a prefix code or a suffix code.

Proposition 9 *Let L be a prefix code or a suffix code. For an integer $n \geq 2$, $P_{L^n} \subseteq P_{L^{n-1}}$.*

Proof. Let L be a prefix code. Suppose that $u \equiv v(P_{L^n})$ and $xuy \in L^{n-1}$. Taking an arbitrary word $w \in L$, we have that $wxy \in L^n$. It follows that $wxy \in L^n$, by $u \equiv v(P_{L^n})$. Hence xvy is in L^* since L^* is right unitary. By Lemma 7, xvy is in L^{n-1} . Similarly we have that $xvy \in L^{n-1}$ implies $xuy \in L^{n-1}$. Thus $u \equiv v(P_{L^{n-1}})$. In the case of a suffix code, we can similarly prove the result. \square

Proposition 10 *Let L be an infix code. Then the following conditions are equivalent:*

- (i) L is a P_{L^2} -class.
- (ii) L^m is a P_{L^*} -class, for two integers m and k with $1 \leq m \leq k$.

Proof. (i) \implies (ii) : Suppose that L is a P_{L^2} -class. First we prove that L is a P_{L^*} -class for every $k \geq 2$. Let u and v be in L and $xuy \in L^k$ for $x, y \in \Sigma^*$. If one of

the two words x and y is in L^* , then the other is also in L^* , since L is an infix code. Then xvy is in L^k by Lemma 7. So assume that neither x nor y is in L^* . Since L is infix, the word u has no proper factor in L . Then there exist $u_1, u_2, z, w \in \Sigma^+$ such that $wu_1, u_2z \in L$, $u = u_1u_2$, $w \in \text{Suf}(x)$, $z \in \text{Pre}(y)$. We have that wvz is in L^2 , so xvy is in L^k since L is a P_{L^2} -class. Similarly we have that $xvy \in L^k$ implies $xuy \in L^k$. Hence L is contained in a P_{L^k} -class for $k \geq 2$. Since $P_{L^k} \subseteq P_L$, L is a P_{L^k} -class by Lemma 8.

Next suppose that $u, v \in L^m$ and $xvy \in L^k$ with $m \leq k$ for $x, y \in \Sigma^*$. Let $u = u_1 \dots u_m$ for $u_1, \dots, u_m \in L$ and $v = v_1 \dots v_m$ for $v_1, \dots, v_m \in L$. Since L is a P_{L^k} -class, $xv_1u_2 \dots u_my$ is in L^k for $v_1 \in L$. Furthermore, for $v_2 \in L$, $xv_1v_2u_3 \dots u_my \in L^k$. Continuing this process, we can prove that for $v \in L^m$, $xvy \in L^k$. Similarly as above, we have that L^m is contained in a P_{L^k} -class. By Lemma 8, L^m is a P_{L^k} -class since $P_{L^k} \subseteq P_{L^m}$.

(ii) \implies (i) : trivial. □

Proposition 11 *For an infix code L , if L^* is a P_{L^*} -class, then L is a P_{L^2} -class.*

Proof. Let $u, v \in L$, and $xvy \in L^2$. There exist u_1 and $u_2 \in \Sigma^+$ such that $u_1u_2 = u$, $xu_1, u_2y \in L$. By the hypothesis, we have that $xvy \in L^*$. Suppose that $xvy \in L^k$ for $k > 2$. Let $xvy = w_1 \dots w_k$ for $w_1, \dots, w_k \in L$. Since L is infix, we have that $|x| < |w_1| < |xv|$ and $|y| < |w_k| < |vy|$. Hence $w_2 \dots w_{k-1}$ is a proper factor of v . This is a contradiction. Thus $xvy \in L^2$. By symmetry, we have that $xvy \in L^2$ implies $xuy \in L^2$, and thus L is contained in a P_{L^2} -class. By Lemma 8 and the fact that $P_{L^2} \subseteq P_L$, the result holds. □

Unfortunately, the converse of Proposition 11 does not hold. For an alphabet $\Sigma = \{a_1^{(1)}, a_1^{(2)}, a_2, b_1, b_2, c_1^{(1)}, c_1^{(2)}, c_2, d_1, d_2\}$, consider the infix code $L = xx_2\Sigma \cup x\Sigma y_1 \cup x\{x_1, u, v_1\} \cup x_2x_2\Sigma y \cup x_2\Sigma y_1y \cup x_2\{x_1, u, v_1\}y \cup \Sigma yy \cup \{uv, vy\}$, where $x_1 = a_1^{(1)}a_1^{(2)}$, $x_2 = a_2$, $u = b_1b_2$, $v_1 = c_1^{(1)}c_1^{(2)}$, $v_2 = c_2$, $y = d_1d_2$, $x = x_1x_2$. It can be easily checked that L an infix code, and L is a P_{L^2} -class. Although both $uvuv$ and $xvvy$ are in L^2 , $xuvvvy$ is not in L^3 since vu is not in L . Alternatively, $xvvy$ and $xuvvvy$ are not in the same class of P_{L^*} .

Next we consider P_{L^n} , $n \geq 1$, and P_{L^*} for s-infix code L .

Proposition 12 *For every s-infix code L , L is a P_{L^2} -class.*

Proof. Let $u, v \in L$. Suppose that $xuy \in L^2$. Since L^* is double unitary, one has that both x and y are in L^* . Then it follows that $x \in L^i$ and $y \in L^j$ with $i + j = 1$ by Lemma 7. That is, either $x = 1$ and $y \in L$, or $y = 1$ and $x \in L$. Thus $xvy \in L^2$. Similarly, it is easily obtained that $xvy \in L^2$ implies $xuy \in L^2$. Thus $u \equiv v(P_{L^2})$. Hence L is contained in a P_{L^2} -class. By Lemma 8 and Proposition 9, L is a P_{L^2} -class. \square

Corollary 13 *For every s-infix code L , and two integers m and k with $1 \leq m \leq k$, L^m is a P_{L^k} -class.*

Proof. It is obvious by Propositions 12 and 14. \square

Proposition 14 *Let L be a s-infix code over Σ . Then L^* is a P_{L^*} -class.*

Proof. Let $u, v \in L^*$. Suppose that xuy is in L^* for $x, y \in \Sigma^*$. Since L^* is double-unitary, both x and y are in L^* . Hence xvy is in L^* . Similarly we have that $xvy \in L^*$ implies $xuy \in L^*$. Thus $u \equiv v(P_{L^*})$, and so L^* is contained in a P_{L^*} -class. Since L^* is a union of P_{L^*} -classes, the result holds. \square

Proposition 15 *Let L be a s-infix code over Σ . Then L^* is contained in a $P_{W(L^*)}$ -class.*

Proof. Let $u, v \in L^*$. Suppose that $xuy \notin W(L^*)$, that is, $L^* \cdot xuy \neq \phi$. Then immediately we have that $\Sigma^*x \cap L^* \neq \phi$ and $y\Sigma^* \cap L^* \neq \phi$ since L^* is double unitary. Hence $xvy \notin W(L^*)$. Similarly we can obtain that $xvy \notin W(L^*)$ implies $xuy \notin W(L^*)$. Thus the result holds. \square

Remark 1 *The result such as Proposition 12 does not hold in general for an infix code: For an infix code $L = \{aba, bab\}$, which is not a strongly infix code, we have that $P_{L^n} \subseteq P_{L^{n-1}}$. However L is not a P_{L^2} -class since the two words aba and bab are not in the same class of P_{L^2} .*

Last we consider the syntactic congruence P_{L^n} of L^n for a strongly outfix code L .

Proposition 16 *Let L be a s-outfix code over Σ . Then every P_{L^n} -class ($1 \leq n$) not contained in $W(L)$ is a s-outfix code.*

Proof. Since the class of outfix codes is closed under concatenation [2], we have that P_{L^n} -class different from $W(L^n)$ is an outfix code by Proposition 5. Moreover it follows that P_{L^n} -class not contained in $W(L)$ is an outfix code by that $W(L^n) \subseteq W(L)$.

Suppose that such a P_{L^n} -class is not s-outfix, that is, there exist $x_1, x_2, z_1, z_2 \in \Sigma^+$ such that $x_1 z_1 \equiv x_2 z_2 \equiv x_1 z_2 (P_{L^n})$ and $x_1 z_1 \neq x_2 z_2$. Since $P_{L^n} \subseteq P_L$, these three words are in the same P_L -class different from $W(L)$. So there exist $w_1, w_2 \in \Sigma^*$ such that $w_1 x_1 z_1 w_2 \in L$, $w_1 x_2 z_2 w_2 \in L$ and $w_1 x_1 z_2 w_2 \in L$. Then we have that $w_1 x_1 z_1 w_2 w_1 x_2 z_2 w_2 \in L^2$, $w_1 x_1, z_1 w_2, z_2 w_2 \in \Sigma^+$ and $w_1 x_1 z_1 w_2 \neq w_1 x_2 z_2 w_2$. This contradicts the fact that L is s-outfix. Thus the result holds. \square

Remark 2 *In Proposition 16, a similar result as Proposition 5 for an s-outfix code L does not hold. That is, P_{L^n} -class different from $W(L^n)$, but contained in $W(L)$, is not necessarily s-outfix. For an s-outfix code $L = \{abbba, baaab, caaac\}$, let $w_1 = abbbabaa$, $w_2 = caaacbaa$, and $w_3 = baaabaa$. Then $w_1 \equiv w_2 \equiv w_3 (P_{L^2})$, but $w_1 w_2$ has a proper outfix $abbbabaa = w_1$ in L . Thus the class which contains w_1, w_2 and w_3 is not s-outfix.*

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